Motivation

- Cheap
- Limited computational and sensing abilities
- Groups of robots
- Fault tolerance
- Parallelism

Overview

Overview:
- One-Time or Repeated Coverage of Known or Unknown Terrain
- Mine Sweeping
- Surveillance
- Surface Inspection
- Guarding Terrain

Structure:
- Motivation
- Theoretical Results
  - Real-Time Search
  - Empirical Results
  - Simulation
  - Actual Robots

Joint work with:
Jonas Svennebring, Boleslaw Szymanski (RPI), and Yaxin Liu
Motivation

You want to build a team of robots that cover terrain repeatedly, for example, to guard a museum at night.

The terrain could be initially unknown.
The terrain could change dynamically.
The robots have very noisy actuators or sensors.
The robots can fail.

Approach 1: POMDP-Based Navigation Architecture

You want to build a team of robots that cover terrain repeatedly, for example, to guard a museum at night.

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Simulator interface to Xavier

Advantages of Navigation with POMDPs

- uniform, theoretically grounded framework
- maintains arbitrary probability distributions over the poses
- explicitly models all uncertainty using probabilities
- utilizes all available sensor data (landmarks, robot movements)
- robust towards sensor errors (no explicit exception handling required)
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Probabilistic Planning

- no location estimates!
- no planning!
- no direct communication!

simpler hardware and software!

- short lived traces
  - alcohol [Sharpe et al.]
  - heat [Russell]
  - odor [Russell et al.]
- virtual traces [Vaughan et al.; Payton et al.]

- long lived traces [Svennebring and Koenig]
Initially, the $u$-values $u(s)$ are zero for all states $s$.

1. $s :=$ start location
2. $s' :=$ a neighboring location of $s$ with a minimal $u$-value
3. $u(s) := 1 + u(s)$
4. move the ant robot to location $s'$
5. go to 2.
The numbers (= markings) coordinate the ant robots!

Theoretical Results (Real-Time Search)

Theorem:
Teams of ant robots that all use the same real-time search method cover all strongly connected graphs repeatedly.

Proof:

Theoretical Results (Real-Time Search)

Korf’s LRTA* cover time guaranteed to be no worse than $O(#\text{vertices} \cdot \text{diameter})$ on any strongly connected graph

[Koenig and Simmons, 1992]
Theoretical Results (Real-Time Search)

Initially, the $u$-values $u(s)$ are zero for all states $s$.

1. $s :=$ start location
2. $s' :=$ a neighboring location of $s$ with a minimal $u$-value
3. $u(s) := 1 + u(s)$
   **or** $u(s) := 1 + u(s')$
   **or** if $u(s) \leq u(s')$ then $u(s) := 1 + u(s)$
   **or** $u(s) := \max(1 + u(s), 1 + u(s'))$
4. move the ant robot to location $s'$
5. go to 2.

- if the strongly connected graphs are directed? yes (see 3 slides ago)
- if the strongly connected graphs are undirected? yes (see 2 slide ago)
- if the strongly connected graphs are undirected grids? unknown

Is the worst-case cover time of a single ant robot that uses node counting polynomial or exponential in the number of vertices (an adversary can choose the graph topology, the start vertex, the goal vertex, and the tie-breaking rule),

- if the strongly connected graphs are directed? yes (see 3 slides ago)
- if the strongly connected graphs are undirected? yes (see 2 slides ago)
- if the strongly connected graphs are undirected grids? unknown

Theoretical Results (Real-Time Search)

Number of robots

Cover time

Korf's LRTA

Wagner's Update Rule

Node Counting

Thrun's Update Rule

[Koenig et. al., 2001]
Theoretical Results (Real-Time Search)

Node Counting

Korf’s LRTA*

Wagner’s Update Rule

Thrun’s Update Rule


Empirical Results (Simulation and Actual Robots)

BORG Lab

[Svennebring and Koenig, 2003]

Empirical Results (Actual Robots)

Ant robots that all use node counting are easy to implement!

Empirical Results (Actual Robots)

Ant Robot Hardware

Thanks to Ashwin Ram for the hardware.

A: trail sensor
B: trail sensor
C: pen
D: micro-controller
E: RS232 interface
our ant robots use a schema-based navigation strategy with an obstacle avoidance behavior and a trail-avoidance behavior.

Our ant robots cover closed terrain even if
- they don’t know the terrain in advance or the terrain changes,
- some ant robots fail,
- some ant robots are moved without realizing this, or
- some trails are destroyed.
Empirical Results (Actual Robots)

The terrain gets saturated with trails over time.

Empirical Results (Modeling with Real-Time Search)

Initially, the u-values $u(s)$ are zero for all states $s$.

1. $s :=$ start location
2. $s' :=$ a neighboring location of $s$ with a minimal $u$-value
3. with probability $(170-u(s))/170$ do: $u(s) := 1 + u(s)$
4. move the ant robot to location $s'$
5. go to 2.

Empirical Results (Simulation)

Empirical Results (Simulation)
Empirical Results (Simulation)

- **TeamBots Simulation of Pebbles with Cleaning**
- **TeamBots Simulation of Pebbles without Cleaning**

**Empirical Results (Simulation)**

- **Terrain Size vs. Coverage Number**
- **Coverage Time vs. Number of Ant Robots**

- **Number of Ant Robots**
- **Cover Time**

**Empirical Results (Simulation)**

- **Terrain Size**
- **Cover Time**

- **25 x 25 meters**
- **10 ant robots**

85 hours without any ant robot getting stuck.
The Future

small infrared tranceivers as smart markers
(similar interesting work is performed at USC and other institutions)

Summary

Real-time search methods provide an interesting means for coordinating single ant robots or teams of ant robots that cover known or unknown terrain once or repeatedly. They leave markings in the terrain, similar to what some ants do. The ant robots robustly cover terrain even if the robots are moved without realizing this, some robots fail, and some markings get destroyed. The robots do not even need to be localized.

Selected Publications

Ant Robotics


Real-Time Search


Additional Information